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Characterization and screening for leaf curl disease resistance in natural variants of tomato (*Solanum lycopersicum*) genotypes

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ABSTRACT

The experiment was conducted during winter (*rabi*) seasons of 2022 and 2023 at ICAR-Indian Agricultural Research Institute, Pune, Maharashtra to evaluate the natural variants of tomato (*Solanum lycopersicum* L.), PTS-8, PTS-25 and PTS-29, isolated from Pusa Gaurav and EC538421. The identified line evaluated along with parental lines (Pusa Gaurav and EC-538421); PTS-24; Pusa Rohini and Arka Rakshak for morphological characterization and tomato leaf curl virus (ToLCV) incidence. Plant height ranged from 41.35–144.33 cm and early flowering (30–33 days) was observed in lines, PTS-24, PTS-25, and PTS-29. Large sized fruits (72–76 g) were recorded in PTS-8 and PTS-25, while highest yield (138.65 t/ha) was recorded in PTS-25. PTS-24 and PTS-25 recorded low seed content of 0.28 g and 0.37 g/100 g fresh fruit, respectively which is desirable for utility in processing industry and for raw consumption. Highest vitamin C content (38.87 mg/100 g FW) was observed in PTS-24. Incidence of ToLCV was lowest in PTS-8 (5.33%), followed by EC538421 (6.25%), PTS -29 (6.61%) and Arka Rakshak (6.93%). Pusa Rohini was most susceptible line (48.42%). All the lines were screened for leaf curl, CMV and aphid/nematode resistance/ tolerance markers with 12 different primers. Line EC538421, its variants PTS-8, PTS-29 and Arka Rakshak showed amplification of resistant fragment (900 bp, T0302 primer) for ToLCV resistant marker *Ty-2*. All the lines were tested negative for other resistance markers. Principal component analysis revealed that traits such as number of fruits/plant, yield, disease intensity, seeds/fruit etc. were some of the principal discriminatory characteristics. These identified lines can be utilized in breeding programmes to develop improved tomato cultivars.

Keywords: Fruit weight, Low seed, Markers, Natural variants, ToLCV, Yield

Tomato (*Solanum lycopersicum* L.) being the most popular vegetable crop is widely cultivated and consumed worldwide as salad and also used in preparation of variety of products. China is the leading producer (67.63 million tonnes) accounting for 26% of the total production, followed by India (21.18 million tonnes). In India, tomato accounts for 11.04% of the country's total vegetables production. Despite of availability of high yielding varieties and hybrids of tomato there is always imbalance in the market demand and supply leading to huge price fluctuations. Losses due to the major pests and diseases caused by various plant viruses are the major reason for losses in quality and quantity of tomato production. Virus diseases caused by tomato leaf curl virus (ToLCV) and tomato mosaic virus (ToMV) cause losses ranging from 90–100% during the dry season. Six resistance genes i.e. *Ty-1* to *Ty-6* are known to provide resistance to ToLCV. *Ty-1*, *Ty-3*, *Ty-4* and *Ty-6* are derived from *S. chilense* accessions (Ji *et al*. 2009, Verlaan *et al.* 2013, Hutton and Scott 2013) while *Ty-2* is derived from *S. habrochaites* (Yang *et al*. 2014) and *Ty-5* from *S. peruvianum* (Hutton *et al.* 2012). The *Tm-2*^{2} resistance gene provides protection against infection with ToMV, while *Mi*-1.2 gene provides resistance against the root knot nematode, aphids and whiteflies (Nombela *et al.* 2003). There is scope to expand domestic production of tomato through breeding programme by developing high yielding cultivars with improved quality (Bergougnoux 2014). Resistant genes for biotic and abiotic stresses tolerance can be identified by exploring tomato germplasm for efficient use in breeding programmes (Al-Shammari and Hamdi 2021). Hence, the present study evaluated the natural variant lines PTS-8, PTS-25 and PTS-29 identified and selected from tomato germplasm with the aim of developing them as promising lines/hybrids.

MATERIALS AND METHODS

The experiment was conducted during winter (*rabi*) seasons of 2022 and 2023 at ICAR-Indian Agricultural Research Institute, Pune, Maharashtra. Seeds of tomato

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genotypes were sown in plug trays in insect proof net house and 30-days-old healthy seedlings were transplanted in the field for evaluating their performance.

Isolation of variants: Plants showing morphologically distinct characters from germplasm EC-538421 and Pusa Gaurav were identified and tagged as natural variants.

Morphological characterization: All the selected variants were separated and self-pollinated and stabilised for six generations to obtain pure lines. The selections were evaluated under field conditions along with parental lines and standard check for yield and disease incidence. The experiment was laid out in a randomized complete block design (RCBD) with three replications and in each treatment 30 plants were transplanted. Among the genotypes, three were released varieties/hybrids (Arka Rakshak, Pusa Gaurav and Pusa Rohini), two were exotic collections (EC-538421 and EC-525138) and four were selections (PTS-8, PTS-24, PTS-25 and PTS-29). Morphological parameters, viz. plant height, days to flowering, fruiting, harvesting etc. were measured in field while quality parameters were recorded after harvesting.

Estimation of seed content: Seeds from each fruit (10 fruits/plant) were extracted separately and number of seeds were counted. Values obtained for each line were used for calculation of seed weight g/100 g fresh fruit.

Qualitative characterization: Total soluble solids (TSS) of fruits was measured using hand-held digital refractometer. Fresh tomato fruits were washed and wiped with tissue paper, and crushed to extract the juice which was then taken with dropper for measurement using refractometer. The ascorbic acid content in fruits was estimated by the method given by Ranganna (1986).

Molecular validation for resistant loci: Young mature leaves (10–15 days old) from each line were collected, cleaned and used for DNA extraction. Genomic DNA was isolated with the help of plant DNA mini kit (Qiagen). Two

Table 1 Plant morphological characters of tomato

	Year	Arka Rakshak	Pusa Gaurav	PTS-8	PTS-24	PTS-25	EC538421	PTS-29	EC528138	Pusa Rohini	CD	CV
Plant height (cm)	2022	116.00	109.67	96.00	40.00	65.67	104.33	144.33	92.00	95.67	14.49	6.33
	2023	95.50	156.86	165.84	42.69	79.94	150.95	210.97	110.25	111.97	22.56	7.56
	PM	105.75	133.27	130.92	41.35	72.81	127.64	177.65	101.13	103.82		
Days to 1st flowering	2022	37.00	33.33	29.33	30.33	29.00	25.67	29.33	33.00	36.67	2.67	4.89
	2023	33.33	27.67	24.67	24.00	24.00	22.00	25.00	25.00	30.00	2.57	5.68
	PM	35.17	30.50	27.00	27.17	26.50	23.83	27.17	29.00	33.33		
Days to 50% flowering	2022	42.00	40.33	37.67	35.00	34.33	31.33	36.00	38.00	41.33	2.41	3.73
	2023	42.67	30.00	29.67	29.00	33.33	28.00	30.00	32.00	31.67	2.87	5.22
	PM	42.33	35.17	33.67	32.00	33.83	29.67	33.00	35.00	36.50		
DFF	2022	48.33	46.33	42.33	40.33	40.33	37.33	42.00	45.00	47.00	2.72	3.64
	2023	45.67	35.33	34.00	34.67	36.33	33.00	32.33	40.00	41.00	2.06	3.23
	PM	47.00	40.83	38.17	37.50	38.33	35.17	37.17	42.50	44.00		
Days to 1st harvesting	2022	79.33	78.00	74.33	71.67	71.67	69.67	74.67	75.67	77.00	3.19	2.47
	2023	77.33	67.67	68.00	56.00	59.67	65.33	64.67	75.33	71.33	2.12	1.81
	PM	78.33	72.83	71.17	63.83	65.67	67.50	69.67	75.50	74.17		
No. fruits/ cluster	2022	6.33	4.67	5.67	6.00	4.67	5.67	5.77	5.11	5.33	1.01	10.73
	2023	7.00	5.67	5.33	8.00	6.00	4.67	5.33	5.67	5.00	1.72	17.04
	PM	6.67	5.17	5.50	7.00	5.34	5.17	5.55	5.39	5.17		
No. of flowers/truss	2022	6.67	5.00	6.67	7.66	6.67	6.33	7.00	7.33	5.67	1.06	9.34
	2023	7.67	5.33	7.00	9.00	8.00	6.33	7.00	7.67	5.33	1.53	12.60
	PM	7.17	5.17	6.84	8.33	7.34	6.33	7.00	7.50	5.50		
No. of fruits/ plant	2022	88.00	73.33	67.00	52.33	60.67	52.67	50.73	208.67	95.00	12.82	8.91
	2023	39.50	52.33	57.67	28.83	65.83	42.67	39.33	73.33	74.17	9.98	10.95
	PM	63.75	62.83	62.34	40.58	63.25	47.67	45.03	141.00	84.58		
Leaf curl disease (PDI)	2022	3.33	15.19	1.33	23.4	14.33	2.4	2.53	20.1	42.33	7.20	29.97
	2023	10.53	39.06	9.33	15.33	14.71	10.1	10.69	37.67	54.51	4.98	12.83
	PM	6.93	27.125	5.33	19.365	14.52	6.25	6.61	28.885	48.42		

PM, Pooled mean.

replicates of each sample were taken and mentioned as A and B in the gel. The amplification of different markers was carried out in Eppendorf Master Cycler Thermal Cycler by following recommended conditions for each primer (Supplementary Table 1). PCR reaction was carried in 25 µl reaction volume and amplified product was run on 3% agarose gel along with ladder (100 bp) and visualized in gel doc system.

The DNA of individual plants was tested for *Ty*-2 marker using T0302 primer which amplifies resistant (900 bp) and susceptible (749 bp) fragments. Based on presence of *Ty*-2 resistant marker (single band of 900 bp) and good horticultural characters, plants were further selected. All the selections/variants and parental lines were also tested for the other six resistant markers i.e. *Ty-1* to *Ty-6,* Tm-2^2 (ToMV, resistance) and *Mi-1.2* (resistance against insect vectors) using specific conditions (Supplementary Table 1).

Field evaluation for disease resistance: Per cent disease incidence (PDI) for leaf curl disease was calculated as per the given formula 30 days after planting against the total number of plants in each genotype and in each replication.

PDI = Number of diseased plants/Total number of plants × 100

Statistical analysis: Data for quantitative and qualitative parameters were subjected to statistical analysis of variance (ANOVA) using SAS 9.3 version software (SAS, USA INC).

RESULTS AND DISCUSSION

The observations were recorded on plant growth characters, yield parameter and biochemical characters of fruits. Lowest plant height was observed in PTS-24 (41.35 cm) followed by PTS-25 (72 cm) and maximum plant height was observed in PTS-29 (144.33 cm), which showed semi-indeterminate type plant growth (Table 1). Minimum days to first flowering and 50% flowering were recorded in EC-538421 with 23.83 and 29.67 days, respectively. The lines PTS-24, PTS-25 and PTS-29 showed early flowering and fruiting in comparison to released varieties and hybrids (Table 1). EC538421 recorded minimum days for first fruiting (35.17) followed by PTS-29 (37.17 days) and PTS-24 (37.50 days). Minimum days required for first harvesting of the fruit was recorded in PTS-24 (63.83 days) and PTS-25 (65.67 days) indicating the earliness of the genotype than its parent Pusa Gaurav (72.83 days).

Table 2 Fruit, yield and biochemical characteristics of tomato genotypes

Character	Year	Arka Rakshak	Pusa Gaurav	PTS -8	PTS -24	PTS -25	EC-538421	PTS -29	EC-528138	Pusa Rohini	CD
Fruit weight (g)	2022	74.69	34.27	73.33	37.38	73.67	36.07	37.30	38.35	58.33	11.26
	2023	83.83	56.36	78.66	56.12	70.40	47.98	61.63	60.23	58.45	16.03
	PM	79.26	45.31	76.00	46.75	72.04	42.02	49.47	49.29	58.39	
Fruit length and circumference (cm)	2022	5.49/15.71	4.18/12.58	3.64/15.03	4.86/11.09	4.77/17.13	3.67/13.60	3.50/13.47	4.18/13.58	3.77/16.20	0.57/1.74
	2023	5.33/15.52	4.01/13.00	4.90/14.11	4.93/11.63	3.87/17.28	4.29/13.87	4.87/12.78	4.58/14.03	4.01/15.86	0.49/0.77
	PM	5.41/15.62	4.09/12.79	4.27/14.57	4.90/11.36	4.32/17.21	3.98/13.74	4.18/13.13	4.38/13.81	3.89/16.03	
Fruit cavity (cm) and locules	2022	5.08/3.00	3.68/3.43	4.59/3.66	3.69/2.89	5.43/3.67	3.90/3.00	4.22/2.08	4.07/2.10	5.23/3.00	0.55/0.46
	2023	5.20/3.00	4.82/3.03	5.30/4.80	4.45/3.47	5.17/3.39	4.30/2.83	5.14/4.58	4.65/2.17	4.80/3.28	0.53/1.18
	PM	5.14/3.00	4.25/3.23	4.95/4.23	4.07/3.18	5.30/3.53	4.10/2.92	4.68/3.33	4.36/2.13	5.02/3.14	
Pericarp thickness (PT)	2022	0.54	0.37	0.45	0.45	0.56	0.53	0.64	0.64	0.60	0.11
	2023	0.72	0.54	0.56	0.57	0.50	0.52	0.46	0.61	0.49	0.06
	PM	0.63	0.46	0.51	0.51	0.53	0.53	0.55	0.62	0.55	
Seed no./ fruit and seed weight g/100 gm fresh fruit	2022	98.33/0.79	117.17/0.69	104.35/1.02	62.17/0.36	87.00/0.21	151.33/1.08	101.04/1.07	91.07/0.54	107.33/0.50	15.59/0.28
	2023	78.75/0.31	119.92/0.57	170.08/0.70	98.39/0.38	107.03/0.36	149.22/0.81	187.28/0.76	98.11/0.34	135.94/0.72	32.53/0.12
	PM	88.54/0.55	118.54/0.63	137.22/0.86	80.28/0.37	97.01/0.28	150.28/0.95	144.16/0.92	94.59/0.44	121.64/0.61	
Yield/plant (kg) and tonnes/ha	2022	3.04/112.84	2.13/79.01	2.08/77.16	1.66/61.48	3.65/135.06	1.83/67.65	2.35/87.16	2.99/110.86	3.10/114.69	0.31/11.77
	2023	3.24/113.90	2.95/109.23	2.04/75.67	1.60/59.45	4.64/142.24	2.05/75.87	2.38/88.27	4.41/118.97	4.36/129.18	0.87/9.85
	PM	3.14/113.37	2.54/94.12	2.06/76.42	1.63/60.47	4.14/138.65	1.94/71.76	2.37/87.71	3.70/114.92	3.73/121.94	
Titratable acidity (%) and TSS (°Brix)	2022	0.21/3.21	0.21/3.57	0.17/5.50	0.13/3.72	0.21/4.44	0.19/4.73	0.17/5.18	0.23/4.21	0.28/3.23	0.01/0.43
	2023	0.22/4.30	0.20/4.21	0.16/4.13	0.12/3.34	0.20/3.54	0.17/5.12	0.16/4.30	0.22/4.17	0.29/4.19	0.07/0.48
	PM	0.21/3.76	0.20/3.89	0.17/4.82	0.12/3.53	0.20/3.99	0.18/4.92	0.16/4.74	0.23/4.19	0.29/3.71	
Vitamin C (mg/100 g FW)	2022	31.02	31.02	23.94	38.49	22.07	17.87	23.62	17.29	18.60	2.69
	2023	18.72	32.42	20.80	39.24	19.82	14.06	22.76	15.88	16.94	2.97
	PM	24.87	31.72	22.37	38.87	20.95	15.97	23.19	16.58	17.77	

PM, Pooled mean; DFF, Days to Ist fruiting.

PTS-24 recorded maximum number of fruits/cluster (7) and number of flower/truss (8.33) in comparison to its parent Pusa Gaurav. A wide variation was found among the genotypes for number of fruits/plants, which significantly varied from 141 in EC-528138 to 40.58 in PTS-24. Among the dwarf lines PTS-25 showed a greater number of fruits/plants (63.25) compared to PTS-24. PTS-8 (76 g) and PTS-25 (72.04 g) recorded high fruit weight whereas lowest fruit weight was observed in EC-538421 (42.02 g). Fruit length ranged from 3.98 cm (EC-538421) to 5.41cm (Arka Rakshak). Similarly, fruit circumference was lowest in PTS-24 (11.36 cm) followed by its parent Pusa Gaurav (12.79 cm) while highest circumference was recorded in Pusa Rohini (16.03 cm). Minimum fruit cavity was observed in PTS-24 (4.07 cm). Locule number is an important phenotypic trait of tomatoes because it affects the shape and size of the fruit. Number of locules in most of the tomato genotypes was approximately three, whereas numbers of locules were two in EC-538421 and EC-528138 and four in PTS-8. Maximum pericarp thickness was observed in Arka Rakshak (0.53 cm) followed by EC-528138 (0.62 cm) (Table 2). Genotypes with thicker pericarp are better to withstand long distance transportation and remain firm for a longer period, when compared to thinly fleshed tomatoes. Differences in the morphology are due to varietal characteristics, which are controlled by their genotypic character and somewhat influenced by the environmental factors of any particular growing area.

Fruit yield is the most important complex trait in tomato. It is influenced by genetic and environmental effects, such as numerous abiotic and biotic stresses. Yield/plant was highest in PTS-25 (4.14 kg/plant), while it was 3.73 kg, 3.70 kg and 3.14 kg/plant for Pusa Rohini, EC-528138 and Arka Rakshak, respectively. Similarly, yield/ha was also highest in PTS-25 (138.65 tonnes), while, the lines Pusa Rohini, EC-528138 and Arka Rakshak produced 121.18, 114.9 and 113.37 tonnes/ha, respectively (Table 2).

Fruit acidity, TSS and vitamin C content are some of important quality attributes in tomato. The level of acidity in tomato fruits is an important parameter associated with sensory attributes like flavour and astringency. Titratable acidity varied significantly between 0.12 in PTS-24 to 0.29% in Pusa Rohini (Table 2). Highest TSS was observed in EC-528138 followed by PTS-8 (4.82) and PTS-29 (4.74). Highest vitamin C content (38.87 mg/100 g FW) was recorded in PTS-24. Both genetic and environmental (growing conditions) factors can contribute to the significant variations in fruit acidity, TSS and vitamin C

The present study identified low seed content in lines PTS-25 (0.28 g/100 g fresh fruit) and PTS-24 (0.37 g/100 g fresh fruit) and maximum in EC-528421 (0.95 g/100 g fresh fruit). Tomato fruits contain seeds in varying amounts. Tomato seed are acidic in nature and intake of raw tomatoes may trigger heartburn for few people. Some of the food product preparations on industrial scale like purée, soups, juices or sauces based on tomatoes may require removal of seeds by various methods, which involves additional processing steps and cost. There are several attempts in fast few years to develop seedless tomatoes (Gillaspy *et al*. 1993). However, there are not many commercially available seedless tomatoes in the market. It may be good idea to develop low seed content fruits without compromising quality. Hence, the identified low seed content lines PTS-24 and PTS-25 will have high utility.

Incidence of ToLCV disease was lowest in PTS-8 (5.33%), followed by EC538421 (6.25%), PTS-29 (6.61%) and Arka Rakshak (6.93%) (Table 1). Pusa Rohini was most susceptible line with 48.42% ToLCV incidence while disease incidence was moderate (14.52%) in PTS -25 and PTS-24 (Table 2). Similar reports were given by Hussain *et al*. (2018) for Pusa Rohini while Arka Rakshak is a hybrid tomato with resistance against ToLCV and other pathogens (Bharathkumar *et al*. 2017).

The exotic accession EC-538421, exhibited two groups of plants having morphologically distinct characters, one group of variants had potato type leaves and other had serrated leaves (Fig. 1). Further, within morphologically similar looking plants, DNA isolated from individual plants also showed variability with respect to presence of *Ty-2* resistant marker. Few plants showed presence of both susceptible and resistance alleles (900 bp and 749 bp bands), some showed only resistant allele (single 900 bp band) and few plants were

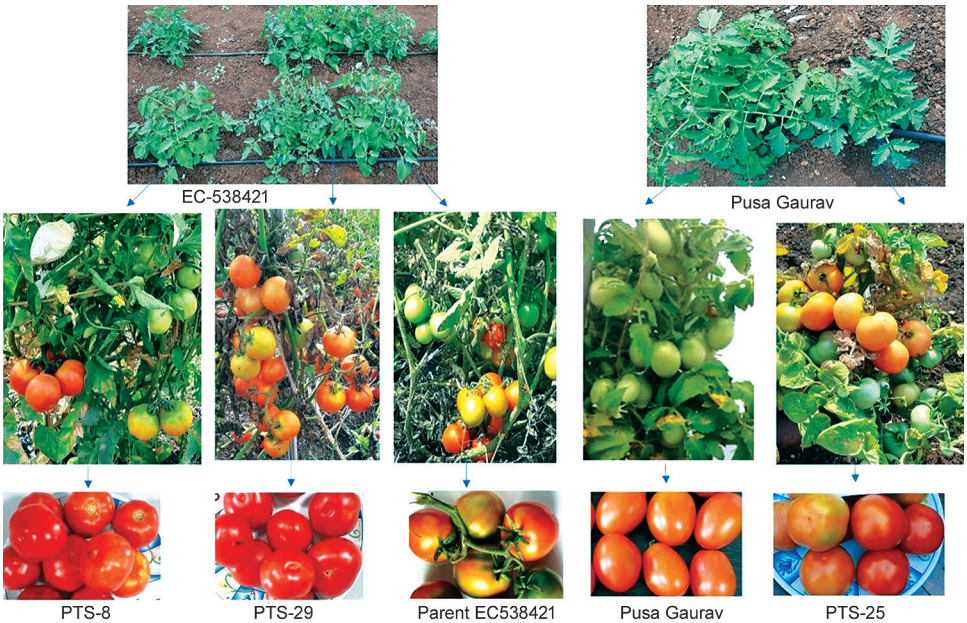

Fig. 1 Tomato variants from tomato germplasm.

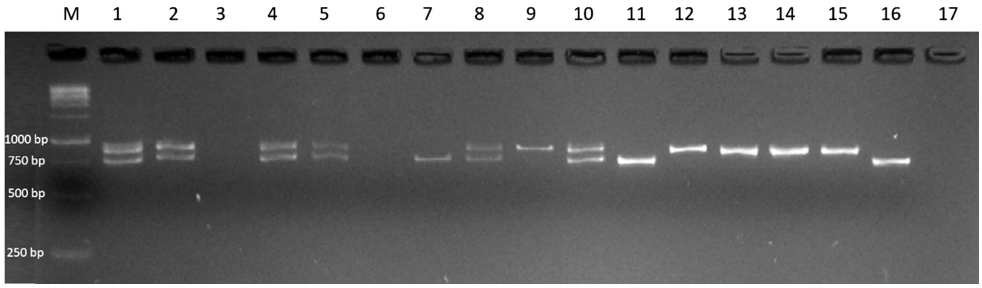

Fig. 2 Individual plants of EC-538421 showing segregation for resistant marker *Ty-2.*

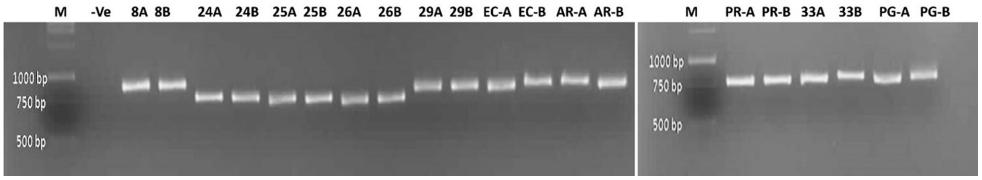

Fig. 3 PCR amplified product from genomic DNA of selected lines with T0302 primer showing resistant (900 bp) and susceptible (749 bp) fragments.
*EC A& B: EC538421, 33 A& B:EC-528138

homozygous for susceptible allele (749 bp) with T0302 primer (Fig. 2 and Fig. 3). The plant no 9, 11,12,13,14 and 15 (Fig. 2) were selected as they showed presence of *Ty-2* resistant marker as single band and from these lines, Pune Tomato Selection-8 (PTS-8) and PTS-29 were identified as promising based on desirable horticultural characters. EC-538421 produces oval shaped fruits with potato type leaves. PTS-8 has potato type leaves, semi-determinate growth and fruit have flat base. PTS-29 has serrated leaves and rest of characters are similar to PTS-8. Similarly, Pusa Gaurav also showed around 4–5 morphologically distinct variants, but for this study only two dwarf variants PTS-24 and PTS-25 were evaluated. PTS-25 are dwarf type plants with fruits having flat bottom, while parent Pusa Gaurav have tall plants which produces "oblong type" fruits (Fig.1). All the selected variants were separated and self-pollinated and stabilised for 6 generations to obtain pure lines.

All the lines were checked for the presence of *Ty* resistance genes *Ty-2, Ty-3* and *Ty-3a, Ty-4, Ty-5* and *Ty-6;* CMV resistant marker Tm-2^2 and insect vector/ nematode resistant *Mi-1.2* genes using PCR amplification with specific primers. Among the different primers used, *Ty-2*: gene specific primer T0302 showed amplification of resistant fragment (900 bp) in tomato lines PTS-8, PTS-29, EC-538421 and in tomato hybrid Arka Rakshak (Fig. 3). In case of EC-538421, DNA extracted from pooled leaf samples showed presence of both susceptible and resistant markers indicating presence of mixture of genotypes (Fig. 2). Hence DNA isolated individual plants selected from EC-538421 were used for identification of plants having *Ty-2* resistant marker. All the lines except PTS-8, PTS-29 and EC-538421 showed susceptible fragments for *Ty2*, *Ty-3* and Mi-1.2 genes. No amplicon was observed with primers specific to *Ty-4* and *Ty-5* suggesting absence of these resistance genes. In case of *Ty-2* markers, only T0302 primer amplified a fragment that could differentiate resistant (900 bp) and susceptible (791 bp) fragments. T0302 (*Ty-2*) has been reported for consistency of amplification in resistant lines (Prasanna *et al*. 2015).

Principal component analysis: Principal component analysis is a simple nonparametric method reducing the dimensionality of the data while retaining most of the variation in the data set. The purpose of the PCA is to obtain a small number of factors which account for maximum variability out of the total variability. In the present investigation, PCA was performed for 23 contributing traits in 9 genotypes of tomato for both the years (Table 3). Out of 23 components only 5 components were taken into account as they showed maximum variation. The first PC contributed 50.18% while 2nd, 3rd, 4th and 5th exhibited 23.11, 14.18, 6.25 and 3.74% of the total variation respectively for the year 2022. Similarly, for the year 2023, PC contributes 64.18, 18.18, 7.53, 4.53 and 2.77% for 1st, 2nd, 3rd, 4th and 5th of the total variation respectively (Supplementary Fig. 1)

The contributions of morphological and biochemical traits for the PC are shown in Table 3. In 2022, morphological traits such as number of fruits/plant (0.95), showed maximum positive contribution towards genetic divergence and the remaining parameters showed very less loadings in PC1. In PC2, only plant height (0.79) and seeds/fruit (0.55) showed positive factor loading. Similarly, in PC3 positive factor loading was observed with yield (0.75) and fruit weight (0.57). PC 4 reflected positive factor loading in seeds/fruit (0.80) and PC5 in disease intensity (0.61), days to first flowering (0.21), days to 50% flowering (0.20) days to first fruiting (0.20), days to first harvesting (0.17) and vitamin C (0.15). Positive contribution indicates significant variation in number of fruits/plant and yield in tonnes/ha hence plays an important role for selection on the basis of quantity.

Similarly, for the year 2023, positive factor loading was observed with plant height (0.80) and yield/plant (0.57) in PC1; dry weight of seeds (0.38), TSS (0.75) and disease intensity (0.29) in PC2; days to first harvesting (0.23) in PC3; number of flowers/truss (0.14) in PC4 and days to 50% flowering (0.17), number of fruits/plant (0.28), days to first harvesting (0.63) and disease intensity (0.57) in PC5.

Number of fruits/plant, yield in tonnes/ha, plant height, seeds/fruit, fruit weight, days to first fruiting, days to first harvesting and disease intensity contributed more positively to PC. Similar results were reported by Hussain *et al.* (2018) and Sehgal *et al.* (2021). Traits coming jointly from different PCs have affinity to stay together, which may be utilized in

Table 3 Contribution of first five principal components for variation in tomato selections

Variable	2022					2023				
	PC1	PC2	PC3	PC4	PC5	PC1	PC2	PC3	PC4	PC5
Plant height	-0.01	0.79	0.20	-0.54	0.53	0.80	0.33	-0.47	0.08	0.02
Days to 1st flowering	0.03	0.00	0.05	-0.04	0.21	-0.01	0.04	-0.04	0.07	0.16
No. of flowers/truss	0.00	-0.01	0.00	-0.01	-0.03	-0.03	0.05	-0.05	0.14	0.14
Days to 50% flowering	0.03	0.01	0.04	-0.06	0.20	-0.04	0.06	-0.02	0.06	0.17
No. of fruits/plant	0.95	0.10	-0.21	0.04	-0.14	0.00	0.13	-0.09	0.03	0.28
No. of fruits/cluster	0.00	0.00	0.00	-0.01	0.01	-0.01	-0.01	-0.01	0.00	0.02
Days to 1st fruiting	0.03	0.02	0.04	-0.05	0.20	-0.01	-0.02	0.00	0.01	0.00
Days to 1st harvesting	0.02	0.03	0.03	-0.06	0.17	-0.02	0.06	0.23	0.62	0.63
Yield/plant (kg)	0.01	0.00	0.02	0.00	0.00	0.57	-0.24	0.75	-0.07	-0.03
Yield/ha tonnes	0.25	-0.07	0.75	0.13	-0.08	0.01	-0.01	0.01	0.01	0.01
Fruit weight	0.00	-0.11	0.57	0.12	-0.14	0.00	-0.01	0.00	0.01	0.03
Fruit length	0.00	-0.01	0.01	-0.01	0.01	-0.01	0.03	0.03	0.03	-0.02
Fruit circumference	0.01	0.00	0.06	0.03	-0.01	0.00	0.00	0.01	0.02	0.01
Pericarp thickness	0.00	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00
Fruit cavity	0.00	0.00	0.02	0.01	-0.01	0.00	0.00	-0.01	0.00	0.00
Locules	-0.01	0.00	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.00
Seeds/fruit	-0.11	0.55	-0.07	0.80	-0.35	0.00	0.00	0.00	0.00	0.00
Dry weight of 100 seeds	0.00	0.00	0.00	0.00	0.00	-0.02	0.38	0.24	-0.27	-0.08
Seed weight (g/100 gm fruit)	0.00	0.01	0.00	0.00	0.00	-0.01	0.03	0.02	0.00	0.00
Biochemical traits										
TSS	0.00	0.01	0.00	0.00	-0.04	-0.14	0.75	0.28	0.25	-0.34
Titratable acidity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vitamin C	-0.06	-0.10	-0.10	-0.14	0.15	-0.03	-0.13	-0.09	-0.06	-0.06
Disease intensity	0.10	-0.17	-0.03	0.07	0.61	-0.04	0.29	0.07	-0.66	0.57

breeding programme to create improvement for yield and quality of fruits (Sinha *et al.* 2021)

Scree plot for component analysis: Further, the scree plot (Supplementary Fig. 2) explained the percentage of variation related with each principal component and demonstrated that the first five PCs explained most of the variation, with less variation accounted by the remaining PCs for both the years. Thus, the traits coming from 5 PCs shows high degree of genetic variation and add for genetic diversity between the genotypes and to exploit in crop improvement programmes.

The present study identified promising lines, viz. PTS-8, PTS-25, PTS-29 and EC-538421 which have potential to develop in to commercial variety or useful in conventional tomato breeding programmes. PTS-25 was identified as high yielding, short height, early flowering and fruiting, with maximum number of large size fruits/plants and low seed content. Lines PTS-24 and PTS-25 were identified with low seed content which is highly useful for processing industry and appreciated for raw consumption. Lines PTS-8, PTS-29 and EC-538421 was identified as resistant to incidence of disease caused by ToLCV. These identified traits can be useful for breeding programmes.

The present research also revealed five principal components, that explained 97.45% variation in 2022 and 97.19% in 2023 of the total variations, thus suggesting that traits such as number of fruits/plant, yield in kg/plant, yield in tonnes/ha, plant height, disease intensity, seeds per fruit etc. were some of the principal discriminatory characteristics. Therefore, the important traits coming jointly from diverse PCs and contributing towards elucidation variability may be kept into consideration during utilization of these traits in breeding programme of tomato.

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